DRILLING AUTOMATION FOR SUBSURFACE PLANETARY EXPLORATION

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ABSTRACT

Future in-situ lunar/martian resource utilization and characterization, as well as the scientific search for life on Mars, will require access to the subsurface and hence drilling. Drilling on Earth is hard – an art form more than an engineering discipline. The limited mass, energy and manpower in planetary drilling situations makes application of terrestrial drilling techniques problematic. The Drilling Automation for Mars Exploration (DAME) project's purpose is to develop and field-test drilling automation and robotics technologies for projected use in missions to the Moon and Mars in the 2011-15 period.

1. INTRODUCTION

Space drilling will require intelligent and autonomous systems for robotic exploration and to support future human exploration, as energy, mass and human presence will be scarce. Unlike rover navigation problems, most planetary drilling will be blind – absent any precursor seismic imaging of substrates, which is common on Earth prior to drilling for hydrocarbons. On the Moon, eventual in-situ resource utilization (ISRU) will require deep drilling with probable human-tended operation [1] of large-bore drills, but initial lunar subsurface exploration and near-term ISRU will be accomplished with lightweight, rover-deployable or standalone drills capable of penetrating a few tens of meters in depth. On the Moon or Mars, drilling will be initially automated, then later human-tended at best. Mass and energy will be scarce. Early development and demonstration of automated drilling technologies is necessary – otherwise, no exploration mission designer will allow a drill on board their spacecraft. The search for evidence of extant microbial life on Mars is expected to require the acquisition of core samples from subsurface depths estimated at hundreds to thousands of meters where, beneath permafrost, the increasing temperature would be consistent with the presence of interstitial water (as a brine) in its liquid phase.

NASA has identified subsurface exploration as a significant science priority; NASA is, therefore, pursuing the technology development program necessary to enable such exploration (including various geophysical measurement capabilities as well as drilling technology).

The Drilling Automation for Mars Exploration (DAME) project's purpose is to develop and field-test drilling automation and robotics technologies for projected use in missions in the 2011-15 period. In this paper, we will discuss the diagnostic approach taken for drill failures and fault identification and recovery, as well as the robotic and executive control aspects of a lightweight, 20kg Mars-prototype drill, shown in Figure 1 in DAME summer Arctic field testing. This includes control of the drilling hardware, state estimation of both the hardware , and the lithography being drilled and the state of the hole, as well as potentially planning and scheduling software suitable for uncertain situations such as drilling. The possibility of significant per-hole drill time reductions and lowered drilling risks exists (perhaps to a few sols per hole, on Mars), if drill automation can be increased to a level comparable to demonstrated Remote Agent-levels [2] or more).

Fig. 1. 20kg Honeybee Mars-prototype drill, tested with vibration sensors in the summer on 2004 on Devon Island, Nunavut, Canada.

DAME includes study and benchmarking of hybrid diagnostic techniques in drill diagnosis, as well as applying fuzzy learning methods to the structural dynamics of drilling systems.[3] The latter is derived from previous work by the authors on identification and control of helicopter shafts and other rotating structures [4]. This paper will describe the application of both approaches. A conditional executive will be adapted from rover applications to provide top-level drill system control and recovery services. It is difficult to accurately predict the level of automation that will be needed for a space-deployed drill without first having experience drilling under realistic analog field conditions. Drill-specific failure modes and software design flaws will become most apparent in the field. This paper will discuss the results of DAME drilling tests in permafrost at a lunar/Mars analog field test site in Arctic Canada.

2. PROBLEMS IN THE USE OF TERRESTRIAL DRILLS IN SPACE

Drilling on Earth is hard – an art form more than an engineering discipline. Human operators listen and feel drill string vibrations coming from kilometers underground. Abundant mass and energy make it possible for terrestrial drilling to employ brute-force approaches to failure recovery and system performance issues. Downhole communications in terrestrial drilling is often via low-bandwidth pulses transmitted through the drilling lubricant (drilling mud), but such an approach is infeasible on cold, low-pressure planetary missions. Terrestrial exploration drilling teams are comprised of specialists at the borehole, each an agent with a role: rigging, drillers, mudders, engineers, loggers, etc. These teams of human specialists come together for each new borehole drilled.

A drill system for planetary deployment will differ in many ways from conventional drilling systems where mass, power and volume are not major considerations and where the speed of penetration is essential for economic operation. On the Moon or Mars, working in a very low temperature/pressure desiccated environment without drilling fluids, the basic task of reliably comminuting the rock and moving the cuttings away from the drill bit and up to the surface will itself be a challenge [5]. The environment will be minimally characterized and we can expect to encounter a range of different rock types ranging from regolith to ice to solid basalts, as shown in Figure 2, without knowing which rock type we will encounter next. Mass considerations prevent the transport and use of drilling mud.

3. AUTOMATION APPROACHES

Some cognitive models see humans comprised as a team comprised of multiple intelligences or agents -- analytical/classificational, emotional, and reactive. Humans can drill on Earth, so a reasonable approach to robotic planetary drilling would be start similarly. In the DAME drilling automation approach, there are several internal agents with defined roles.

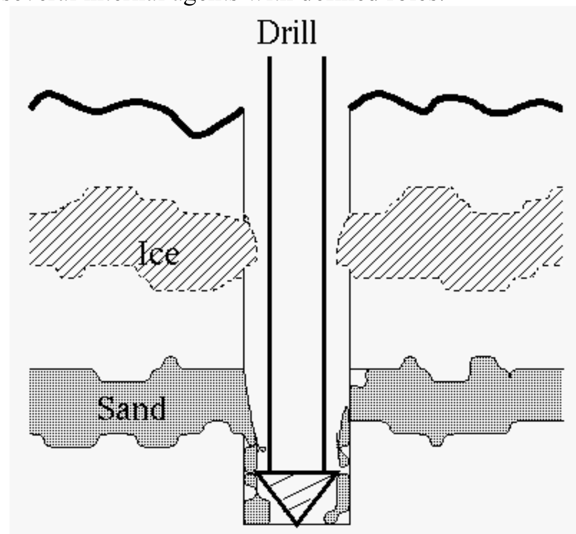

Fig. 2. Subsequent drilling strata are likely to be unknown in planetary drilling scenarioes.

An equivalent to quick-reflex is implemented as very fast heuristic rules or sensor limit-checks. A fuzzy neural net uses its past training examples of known drill hardware problems or faults and then perceives and matches known fault vibrational signatures to incoming data. A model-based reasoning module contains an internal first-principles simulation of drill structure and behaviors, and is invoked when there's a novel fault or situation that the other agents can't handle. An overall executive takes the hypotheses from the neural or model-based agents, and weighs between them and decides what course of action to invoke and how it can be made to be compatible with the drilling operations' higher-level goals.

4. PROCEDURE – DRILL AUTOMATION DESIGN

Lightweight dry drills may break or become stuck quickly in some failure modes, or may degrade progressively in others (such as ice-necking or bit wearout). And the layers being drilled are not know a priori… so some apparent wearout or rapid drill faults may actually reflect penetration into the next layer of material (with different mechanical properties). Our approach is to apply three types of automation:

(a) real-time limit-checking and safing, using a rule-based approach to monitor motor torques and temperatures;
(b) near-real-time vibration measurement and fast frequency-domain pattern-matching using a neural net; and

(c) in-line prognosis of degradation and wearout using model-based reasoning.

Part (a) is being implemented in the drill executive and control software, while (b) and (c) will be separate diagnostic/prognostic software modules.

4.1 Neural-fuzzy interpretation of vibration

The process of identification of the state of the system will be based on two different identification techniques. The two methods shown in Figure 3 include model-based identification procedures with uncertainty models. The second method uses fuzzy neural network techniques. The fuzzy neural network techniques will be used to interpret the vibration patterns -- then directing the model based identification technique to specify fault sub-categories, like whirl mode or stick-slip mode or hard-target/worn bit.

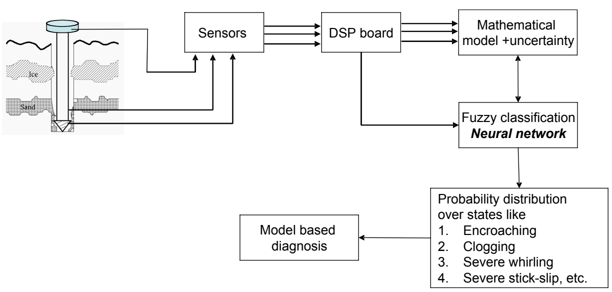

Fig. 3. Monitoring and diagnosis/prognosis architecture.

4.2 Model-based reasoning

Looking at issues of diagnosis and control for planetary drilling equipment, our technology emphases are on reasoning under uncertainty and robust operation of hands-off drilling. There are potentially issues in multi-agent coordination, as well as adjustable levels of autonomy. Long-term use may also lead to model changes (due to part wear, failures, repair by astronauts) that must be adapted to -- so adaptive models are needed; model learning could also be applied to this problem.

The current model-based reasoning approach focuses on the primary drill failure modes, which include auger choking and hard material/worn bit. As a result, the drill model, shown in Figure 4, has been simplified to only model those components that directly impact predictions for the given failure modes.

It is logically oriented such that input to output progresses from left to right at all levels. In addition, the entire model is encapsulated in a higher level, composite component that facilitates the transition from external to internal variables; this makes all internal modifications transparent to external components, such as the diagnostic manager. All component behavioral equations, upon which the model is based, have had their parameters adjusted to fit the field data.

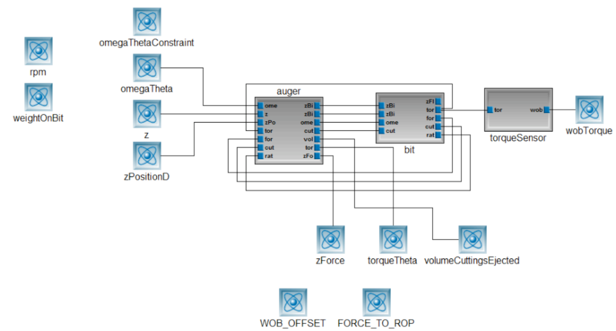

Fig. 4. Diagnostic component model for the DAME drill.

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4.3 Data communications over a software bus – MInI

4.3.1 Background

The MARTE Instrument Interface (MInI) is a simple and flexible communications package, based on a subset of CORBA, that was originally developed to ease the software development and integration process for the Mars Astrobiology Research and Technology Experiment (MARTE) [6,7]. MARTE is a complex, multi-national project that is developing and demonstrating an integrated drilling, sample handling, and science payload in order to simulate a Mars drilling mission. The MARTE project has many instruments and control systems being developed across a number of widely separated institutions in Spain, Texas, California, Oklahoma, and New York. All of these pieces needed to be developed independently at the home institutions, but yet come together during a short integration period and communicate across a number of different platforms. MInI was developed in order to facilitate this process [8].

4.3.2 DAME Use of MInI

The DAME project has leveraged the work done on MInI in order to facilitate communications between the elements in its architecture. Figure 5 shows the overall DAME software architecture. The DAME architecture consists of an executive, MInI instrument dispatcher, drill server, diagnosis modules, diagnostic user interface, and drill controller.

The purpose of the contingent executive is to send commands to the drill based on the state estimates it is receiving from the two diagnostic modules. It is purely a MInI client module, in that it sends commands and information requests to the other servers. Likewise, the diagnostic user interface is a client that allows a user to monitor the state of the system by requesting state estimates directly from the diagnostic modules. The diagnostic modules themselves continuously monitor the state of the system by receiving data from the drill server, and reasoning about this data in order to provide state estimates. The drill server receives data from the low level drill controller and provides this information to the other servers by either publishing the information (i.e., via the middleware), or answering direct queries. It also relays the commands from the executive to the low level drill control and device drivers.

The DAME diagnostic modules and drill server are a departure from a typical client/server architecture, in that these modules must act as both clients and servers. The reason for this is that the vibration classification diagnostic module prefers to receive data from the drill server upon request. That is because it does periodic estimates based on occasional data samples. On the other hand, the model based diagnosis module continuously receives the data from the server in order to track the system with its internal model.

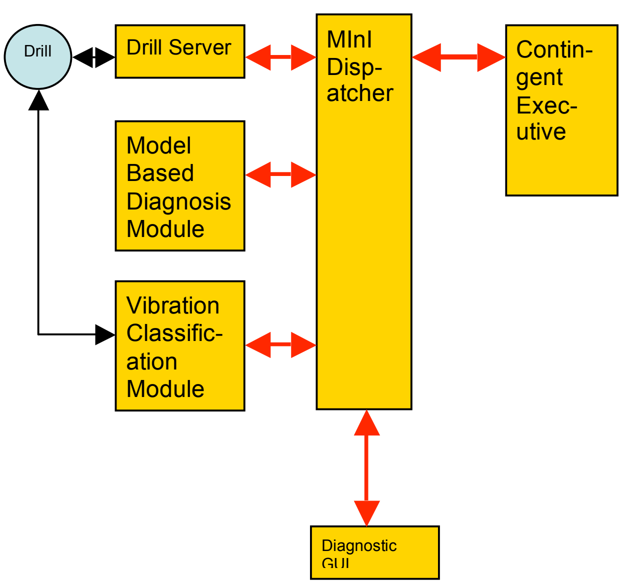

Fig. 5. MInI architecure integrating the DAME diagnostic modules with the drill.

4.3.3 Real-time considerations

For an automated planetary drill to fly, it must be capable of real-time self-monitoring and fault recovery, given lightspeed time delays and probable intermittent communications to Earth. Real-time operations are typically defined in drilling in terms of seconds, rather than millisecond-order required in some spacecraft control applications.

While trained neural nets are fast – used in many terrestrial realtime applications – acquiring vibration patterns is not. Structural identification requires the use of accelerometers and/or laser vibrometers for several measurements lasting a few seconds each, averaged and stacked and filtered prior to Fourier transforming to get the frequencies and mode shapes. In some sense, the time needed to observe the drillstring vibrations neutralizes the processing-speed advantages of a connectionist approach. On the other hand, model-based reasoning has a non-real-time reputation – but that is less so in slow-changing drilling applications, the models have few components, and time-domain sensors (such as measuring motor currents or temperatures) can be sampled faster than the vibration characteristics.

So both diagnostic approaches are complementary in the DAME approach, each doing one diagnostic activity well. To insure safe operations, the DAME drill controller in Figure 5 also implements rule-based sensor limit checks.

5. RESULTS

The DAME project is underway, leading to a planned completion at the end of 2006. In the first year, a modified lightweight Honeybee Deep Drill was designed for use in low-power drilling in permafrost and regolith-like fallback breccias. This full-scale prototype planetary drill was deployed to Haughton Crater on Devon Island, Nunavut, Canada in July 2004 for initial field tests. The purpose of the 2004 DAME tests were to demonstrate and characterize both drill faults (for developing diagnostic models and training examples) as well as refine nominal drilling operations and refine the drill design. This milestone marked the first time a flight-sized prototype drill had been tested under field conditions at a high-fidelity Mars-analog site (Haughton Crater).

The drill was deployed at two sites at Haughton Crater, operating at Mars-relevant power levels (max150-200W). Over eight days, it drilled 2.2m in permafrost and the regolith-like breccia found in the Haughton impact crater. Eight drill faults were demonstrated during testing, as well as nearly 50 hours of nominal operations. Drilling operations were halted periodically in order to capture the vibrational signature of the drill at different depths/lengths, as shown in Fig. 6.

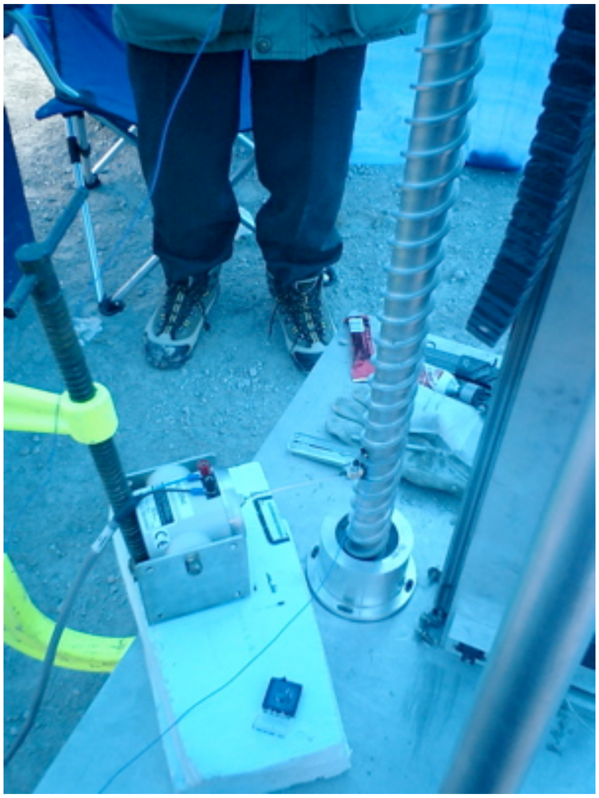

Fig. 6. Vibrational signatures of the drill shaft, acquired in 2004 tests, have been used in model development.

All objectives for the 2004 field season were met, including drill design refinement. In the latter area, cuttings-removal proved to be a problem, as frozen cuttings would thaw on the auger flutings as they approached the above-freezing surface ambient. These thawed cuttings formed a fine mud which clogged further cuttings-removal, but would not be an issue in actual lunar or Mars drilling environments. In addition to testing drill operations, the DAME team integrated the Honeybee control software with the initial NASA-developed Conditional Executive and ran simple drilling plans. This was intended as a 2005 goal – the DAME plan is to add observe-only diagnostics and monitoring in summer 2005 tests at Haughton, leading to the DAME software in control of drilling in the summer of 2006.

6. CONCLUSIONS

The search for resources and past/present life on other planetary bodies will require subsurface access, which requires exploratory drilling. Drilling has been a hard, human-intensive problem in terrestrial applications, but planetary drills require automation. The DAME project has taken significant initial steps toward developing an architecture, two complementary diagnostic approaches, and field tests leading to drilling automation. Realtime issues in vibration analysis for drill diagnosis may require additional study, but component model-based approaches seem to have adequate performance for use. Continued 2005 and 2006 development and field tests are promising.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Glass, B. and G. Briggs, “Evaluation of Human vs. Teleoperated Robotic Performance in Field Geology Tasks at a Mars Analog Site,” *Proceedings of iSAIRAS 2003,* Nara, Japan, May 2003

2. Bresina, J. L, et al., “Increased flexibility and robustness of Mars rovers”, *Proceedings of i-SAIRAS '99, The 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, 1999.

3. Glass, B. et al., “Automation Architectures for Smart Lander Drilling”, *NASA Ames Research Center, Computational Sciences Division, Technical Report*, March 2002

4. Luo, H, and Hanagud,S., “ Damage Detection and Health Monitoring of Structures by Using Dynamic Response and Neural Networking Techniques” , Georgia Institute of Technology, School of Aerospace Engineering, *Technical Report*, 1996

5. Blacic, J., and Dreesen, D. Mockler, T, “The 3rd Dimension of Planetary Exploration – Deep Subsurface Drilling”, *AIAA Space 2000 Conference and Exposition*, Long Beach, 19-21 September, 2000, Paper AIAA-2000-5301.

6. C. Stoker, et al., “Mars Analog Río Tinto Experiment (MARTE): 2003 Drilling Campaign To Search For A Subsurface Biosphere At Río Tinto, Spain,” *35th LPSC*, Abstract 2025, 2004.

7. C. Stoker, et al., “Field Simulation Of A Drilling Mission To Mars To Search For Subsurface Life,” *36th LPSC*, Abstract 1537, 2005.

8. “MInI User’s Guide,” H. Cannon and M. Branson, Version 1.0, Computational Sciences Division, NASA-Ames Research Center, Moffett Field, CA, March 2005.